Presentation Start

Why Hydrogen? Building an Infrastructure

Jay Keller, Ph.D.
Department Manager
Combustion in Engines and Hydrogen Energy
Combustion Research Facility
Sandia National Laboratories

Stanford
G-CEP Workshop

April 14-15, 2003

What are the issues we trying to solve?

- Energy security – transportation's dependence on petroleum
  - Increasing dependence on foreign oil, particularly from unstable regions
- Vulnerable domestic & international energy infrastructures
  - Oil and natural gas pipelines
  - Few and vulnerable ports of entry
- Urban air pollution
  - Criterion gas emission (NO_x, HC, PM, CO …)
- Threat of climate change
  - Atmospheric concentration of [CO_2], [CH_4] …

Fuel Use by End Use Sector (Percent Share)

	Electricity	Transportation	Residential
Coal	48		
Oil	3	96	8
Natural Gas	17	3	27
Hydro	9		
Electricity		1	62
Renewable			3
Nuclear	19		
Solar	2		
Hydrogen		x	
Wind	2		

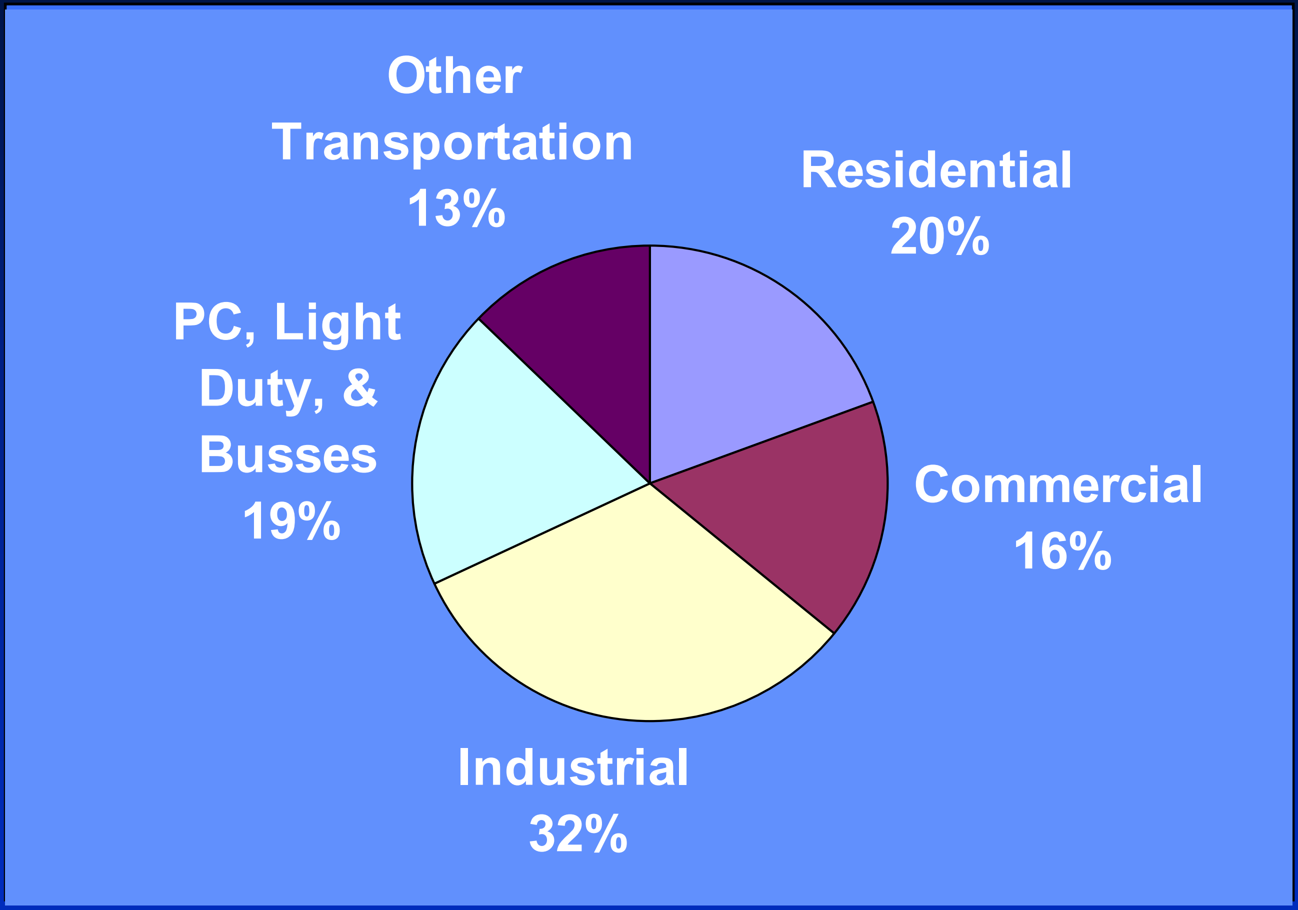
Stabilizing Atmospheric CO_2 Concentrations …

- **The residence time for CO_2 in the atmosphere is on the order of 120 years ***
  - **The concentration of CO_2 in the atmosphere is a result of cumulative net emissions ****
    - From pre-industrial times to the indefinite future, by every economically developing country, everywhere on the planet . . . and with most emissions yet to come **
- **Net Emissions must eventually decline to virtually ZERO . . . whatever the concentration target might be. ****

** *Stabilizing Atmospheric Carbon: The NCCTI Challenge,*
Jae Edmonds, John Clarke
NCCTI Integration Group
Measurement, Monitoring and Validation Workshop, September 26, 2001

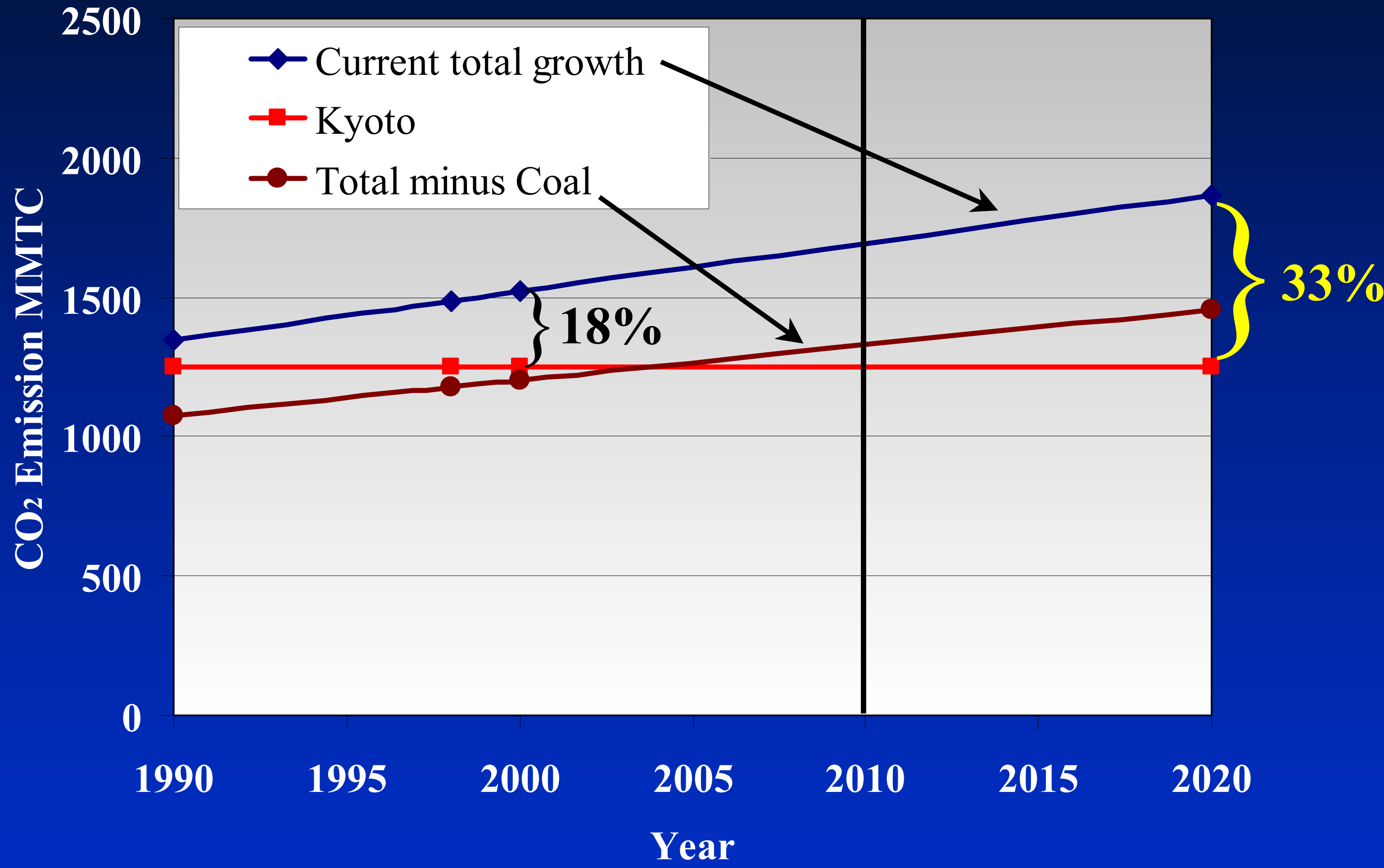
* Combustion's Impact on the Global Atmosphere,
M. J. Prather, J.A. Logan
25th symposium (International) on Combustion/The Combustion Institute
1994/pp 1513-1527

CO_2 Emissions by Energy Sector



Source: AEO '99, USDOE OTT

U.S. Carbon Emissions



Source: DOE/EIA AEO 2001

Solutions

- Dependence on Petroleum
  - Hydrogen, natural gas, coal and/or bio-fuels
- Energy supply vulnerability
  - Use hydrogen as an energy carrier made from the broadest spectrum of domestic energy feed stocks
    - fossil fuels and coal (with CO_2 sequestration), renewables …
- Urban air quality (criterion gas emission)
  - Conventional fuels with after treatment
  - Natural gas fueled vehicles with after treatment
  - Hydrogen fueled vehicles with or without after treatment
- Climate change
  - Hydrogen and/or bio-derived energy carriers

Vision for the Hydrogen Economy

"Hydrogen is America's clean energy choice. Hydrogen is flexible affordable, safe, domestically produced, used in all ***sectors*** of the economy, and in all regions of the country."

National Hydrogen Roadmap

- **Major Findings**
  - **"… Widespread use of hydrogen will affect every aspect of the U.S. energy system from production through end-use. …"**
- **Conversion**
  - **"… Conversion of hydrogen into useful forms of electricity and thermal energy involves the use of fuel cells, reciprocating engines, turbines, and process heaters. … "**

National Hydrogen Roadmap (cont)

⇨ Conversion

- " … Government should assist in developing better information on the fundamental properties of hydrogen combustion and … materials, electrochemistry, and interfaces for fuel cells."

⇨ Applications

- "… Ultimately, consumers should be able to use hydrogen energy for transportation, electric power generation, and portable electronic …"

Hydrogen End-use

- Hydrogen enables operating conditions not possible with hydrocarbon fuels – for example:
  - **Stable combustion at much higher dilution levels**
    - **Enables premixed dilute stable combustion to occur below the knee in the NO_x curve**
      - Reciprocating ICEs, Turbines, Process Heaters …
  - **Effective octane rating is high**
    - **Enables higher compression ratios and still operate spark ignited**
  - **Enables fuel cells**

Requirements on hydrogen conversion technologies for vehicular use

- Highly efficient energy conversion
- Power density must be sufficiently high to be packaged in a vehicle
- Environmentally benign
- Cost effective hardware
- Compatible with existing infrastructure
  - manufacturing, service, supplies, maintenance
  - refueling
- Energy storage density sufficiently high to provide acceptable range

What is possible for an optimized ICE?

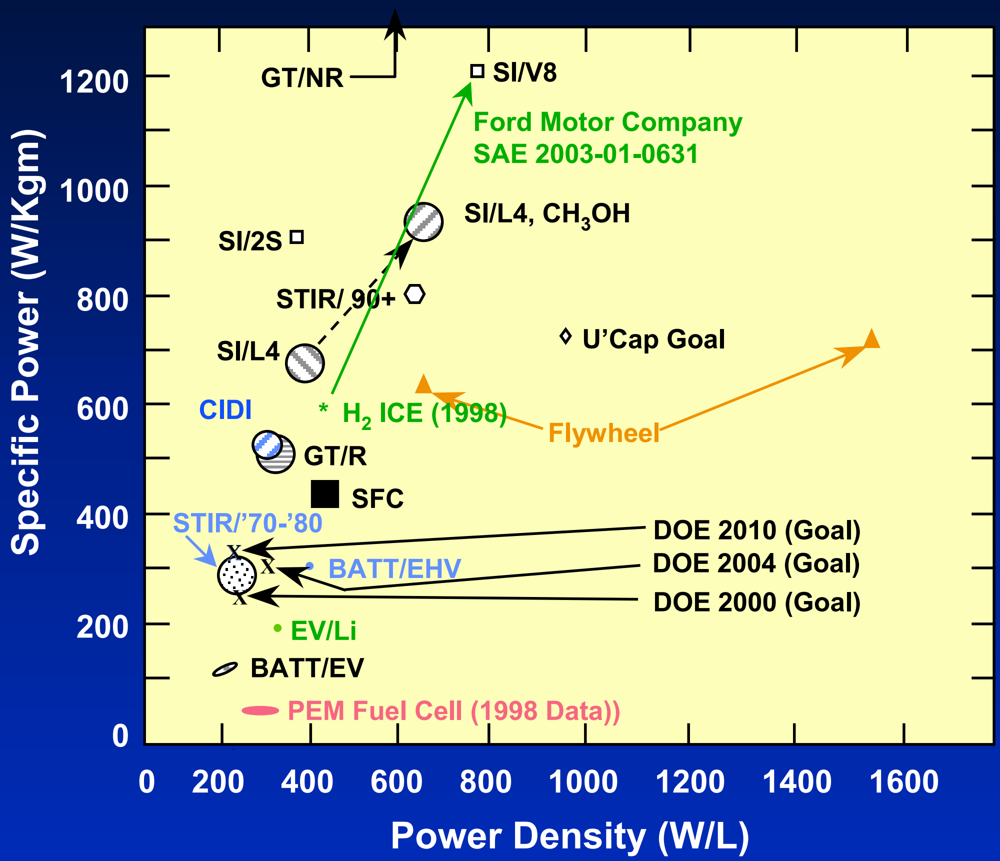
- **Measured peak efficiencies ***
  - **Indicated ~ 52%, brake ~ 37%**
- **H_2 ICEs are cost competitive with current gasoline ICE powertrains ***
- **HC, CO all near zero engine out emissions ***
  - **Trace amounts from lubricating oil**
    - **CO – O(1) ppm, HC – O(5) ppm for a reduction of a factor of 1000, 250 respectively compared to gasoline tailpipe emissions**
- **Engine out Dial-a-NOx value ~ 5-6 ppm**
- **With after treatment NOx values can be near zero ****
  - **Measured tailpipe NOx emissions equal to ambient levels of about 50 ppb**

•SAE Papers #'s 2002-01-0240 thru 0243 and 2003-01-0631; Ford Research

**James Heffel, University of California, Riverside, College of Engineering – Center for Environmental Research and Technology (CE-CERT); Personal Communication

Under the technical guidance and contract to Sandia National Laboratories, funding from the Hydrogen Program Office; OPT

System Power Densities



Mass and space requirements for energy-conversion and energy-storage devices. (Based on engine rated / max-power condition)

KEY:

SI / L4 = 4-stroke spark ignition, Fe-block L4
SI / 2S = 2-stroke spark ignition, AL-block L3
SI / V8 = 4-stroke spark ignition, AL-block V8
CIDI = direct injection turbocharged diesel
GT / R = regenerative gas turbine, circa 1950-70
GT / NR = nonregenerative gas turbine, circa 1950
STIR /'70-'80 = Stirling, circa 1970-80
STIR /'90+ = Stirling (swash-plate), circa 1990
BATT / EV = current batteries for electric car
EV / Li = anticipated lithium electric car battery
BATT / EHV = Pb-acid battery for hybrid vehicle
FLYWHEEL = electro-mechanical battery
U'CAP GOAL = goal for ultracapacitor
SFC = Solid Oxide Fuel Cell (500ºC)
H_2 ICE= Lean burn optimized ICE - AL block

DOE Goals are for the PEMFC system excluding the fuel processor

Original source: SAE International Magazine modified by Jay Keller, SNL

Range and Mileage ?

Vehicle	Storage Mode	Internal Vol (l) *	H_2 (kg)	Mileage (mpgge)	Range (miles)	Ref
Ford Model U	**10,000 psi**	180	**7**	**45**	**300**	[1
Ford P2000 – ICE	**3600 psi**	**87**	**1.5**	**31.4/46.7**	70	[2]
BMW 750hL – ICE	**Liquid**	**140**	9.9	22	**218**	[3]
Ford Focus FCV	**5000 psi**	**186**	4.3	47	**200**	[4]
Toyota FCHV	**3600 psi**	**136**	3.2	57	**182**	[5]
Honda FCX	**5000 psi**	**157**	**3.8**	45/58	**170/220**	[6,7]
Chrysler Natrium	**$NaBH_4$**	**200**	10	**30**	**300**	[6]
GM HydroGen3	**Liquid**	**68**	**4.5** **4.8**	55 50	**250** **240**	[6,7]
GM Hy-wire	**5000 psi**	88	**2**	40	**80**	[7]

BMW 750 HL

Toyota FCHV

Ford P2000

*** Does not include tank system volume**

Where are we going?

- **Some FreedomCAR Technical Targets (2010)**
  - **Reciprocating H_2-ICE**
    - **Cost - $45 / kW**
    - **Peak brake engine efficiency of 45% and must meet or exceed all emissions standards**
  - **PEM Fuel Cell System**
    - **Cost - $45 / kW**
    - **Peak break thermal efficiency of 45% and must meet or exceed all emissions standards**
      - Does not include vehicle traction
      - Includes FC BOP, fuel processor subsystems and auxiliaries
    - **325 W/kg power density and 220 W/L specific power on hydrogen (not reformate!)**
    - **15-year life capable of 55 kW for 18 seconds and 30 kW continuous**

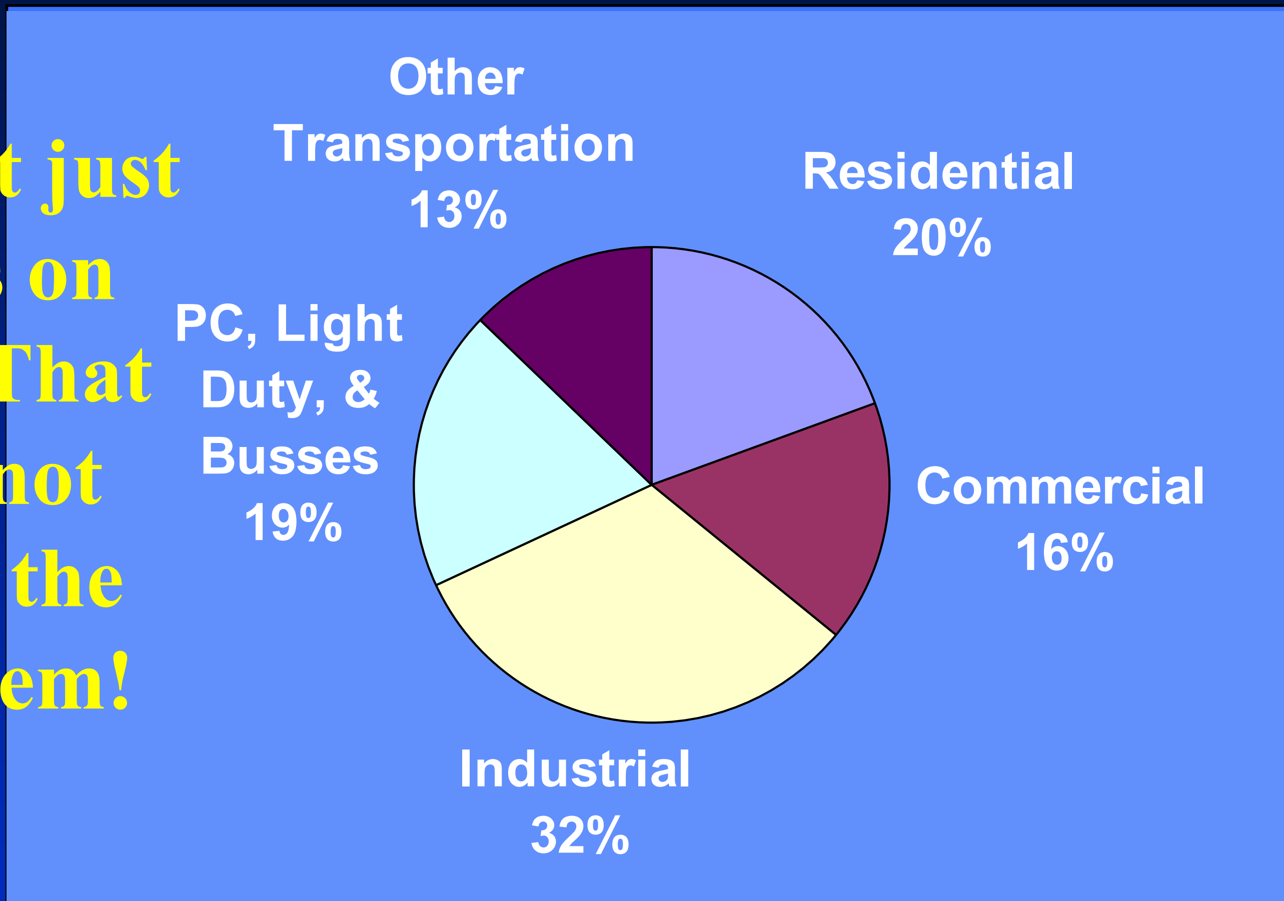
Some Technical Challenges Today?

- Reciprocating H_2-ICE
  - Improve power density
    - while it is good some feel it is not good enough
  - Improve efficiency
  - Pre-ignition at low diluent levels
  - Materials compatibility
  - Lubricity
- PEM Fuel Cell Systems
  - Cost
    - DOE's program is focusing on PEM Fuel Cell cost reduction
  - Power density and specific power
  - Catalysts loading – eliminate precious metal catalysts?
  - System efficiency – BOP and power conditioning
  - Manufacturability – Mass production
  - <u>*Low Temperature Starting/Operation – Water Freezes*</u>

Remember This ?

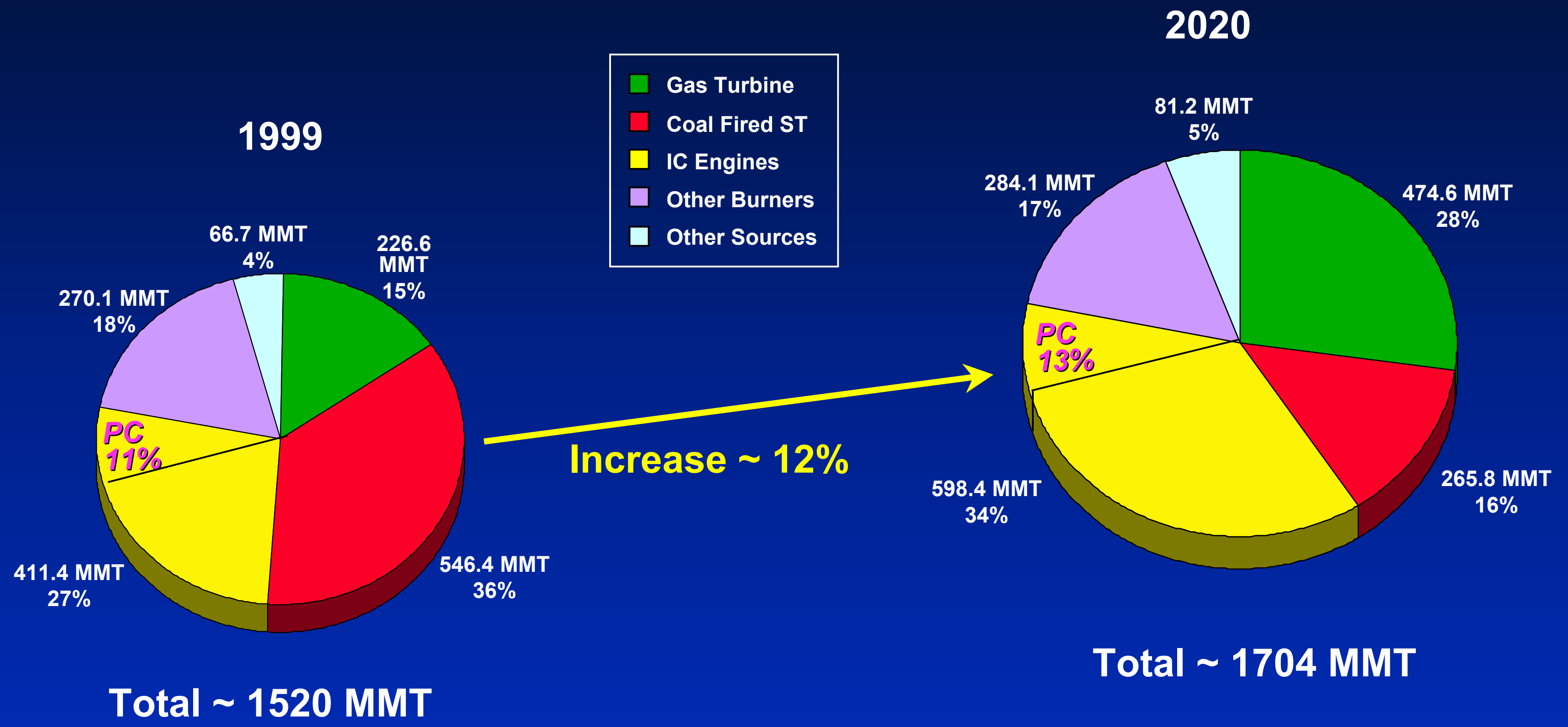
CO_2 Emissions by Energy Sector

Cannot just focus on PCs! That will not solve the problem!



Source: AEO '99, USDOE OTT

U.S. CO_2 Emissions by Combustion Source



⇨ Gas Turbines are the fastest growing power production technology

Source: Analysis of Strategies for Reducing Multiple Emissions from Power Plants: Sulfur Dioxide, Nitrogen Oxides, and Carbon Dioxide, EIA, Dec 2000.

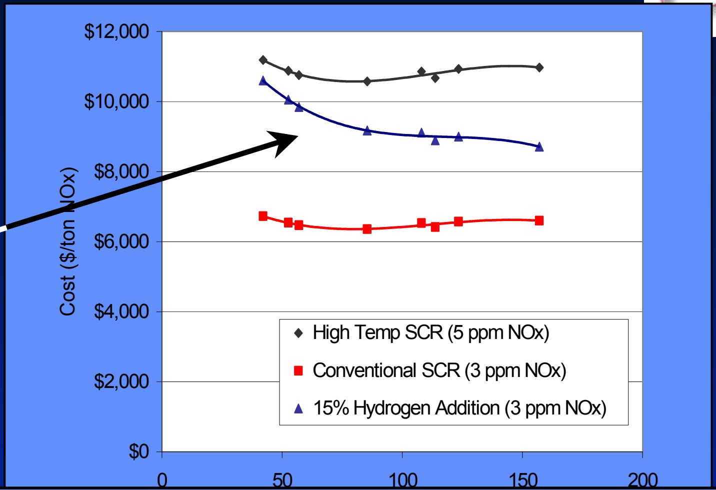
Hydrogen-Enriched Turbines

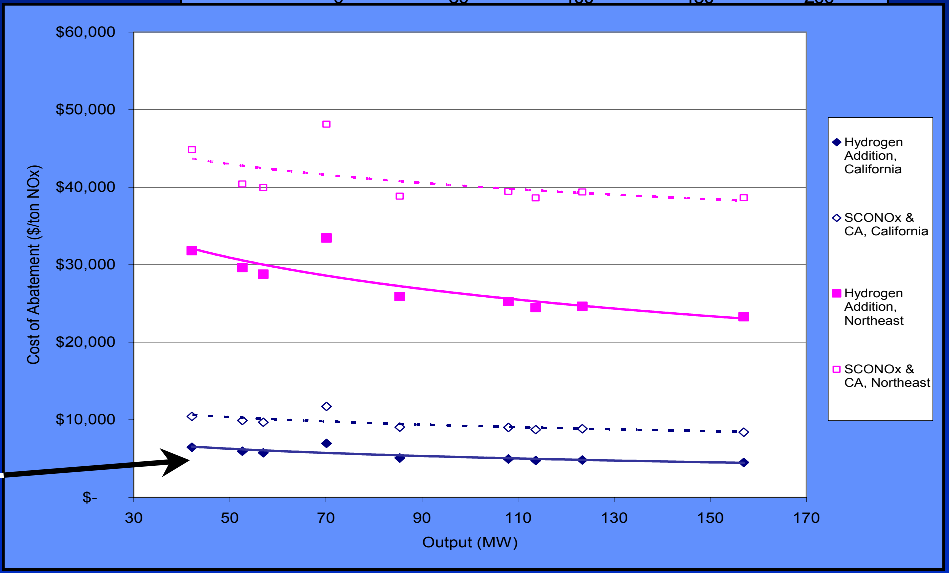
⇨ Drivers

- H_2-blended approach provides a solution to contemporary problems and provides a transition strategy to a carbon-free H_2 energy system
- Alternative low- and medium-heating value fuels containing H_2 could provide a significant source of cost-effective fuels
- Gas turbines are the fastest growing power production technology
- Gas turbines are responsible for about 15% of the U.S. CO_2 budget and are anticipated to grow to 28% in the next 20 years
- Fewer number of stationary turbines (compared to PCs) representing a larger impact on CO_2!

Economic Analysis for Emissions Control

- NO_x abatement
  - Cost comparisons with Dry Low NOx combustors and Selective Catalytic Reduction showed 15% H_2 addition cost competitive
  - Less than 3 ppm NOx achievable with 15% H_2 addition
  - H_2 addition up to 20% offers NOx levels below 1 ppm
- NO_x plus CO_2
  - @ 65% H_2 addition resulting in less than 1 ppm NO_x and a 65% reduction in CO_2 -- including emission credits H_2 addition is cost competitive for all turbine sizes analyzed (30 to 170 MW)





Some Technical Challenges Today?

- **Lean Combustion Systems**
  - **Turbines**
    - **Acoustic instabilities**
    - **Flame stability**
      - Flashback and Blow off
    - **Robust systems capable of handling variable fuel properties**
      - variable hydrogen concentration
    - **Materials compatibility**
  - **Process heaters and boilers**
    - **Acoustic instabilities**
    - **Flame stability**
      - Flashback and Blow off
    - **Materials compatibility**

Challenges to Building an Infrastructure

- **Public education**
- **Safety**
  - **Learn how to handle H_2 safely with the general public**
  - **Developing useful codes and standards for H_2 installations**
  - **Use H_2 safely in a wide variety of applications**
    - **Commercial, Residential, Utility, and Transportation**
- **Production**
  - **Distributed and centralized production (with carbon management if source is fossil fuels)**
- **Storage**
  - **Stationary -- Small and Large scale**
  - **Mobile -- Ground, water and air**

Challenges of Building an Infrastructure

- **Develop efficient end-use conversion technologies**
  - **Conventional combustion technologies, Advanced fuel cell technologies**
- **Delivery**
  - **Net work of pipes and other ground transportation**
- **Personnel Training**
  - **Maintenance workers**
  - **Fire Marshals and Code Officials**
- **Maintenance network**
  - **Parts distribution**
  - **Repair facilities**
- **Etc.**
- **Oh Yeah – refueling stations for PCs**

The building of an infrastructure Make Everyone a Winner

- **Evolutionary not revolutionary – driven by market forces (characteristic time > characteristic economic time scale – quesi-steady)**
  - **Introduce H_2 as an energy carrier into existing energy infrastructure preserving the installed capital base**
    - **Utilize conventional conversion devices modified for optimal hydrogen use in all energy sectors**
  - **Focus on high payoff applications for both CO_2 and for generating an energy market demand for H_2**
- **Introduce advanced H_2 under market conditions that provide a pull …**

One Mans View - Mine

Gaining public acceptance

"We can start developing the hydrogen infrastructure as we perfect the fuel-cell car; and the internal combustion engine can run rather well on hydrogen … , the ICE hydrogen car is not the enemy of the fuel cell,"

"Indeed, if we were starting to deploy hydrogen-powered ICE cars tomorrow, it would hasten the day when fuel cells were viable because it would help bring the hydrogen infrastructure into place sooner rather than later. "

- David Freeman

Chairman, California Power Authority

Presentation End